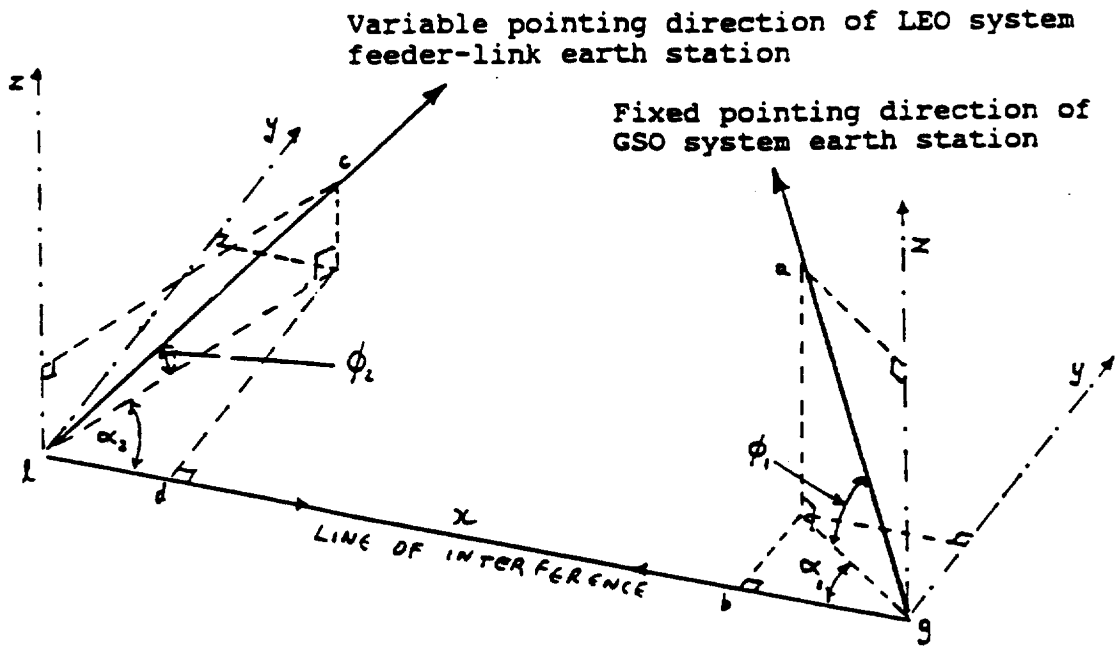


Then the joint antenna discrimination contains the term 25Log(<agb) + 25Log(<cℓd) dB,

Using spherical trigonometry $\text{Cos}(\angle agb) = \text{Cos}(\phi_1).\text{Cos}(\alpha_1)$,
and $\text{Cos}(\angle c\ell d) = \text{Cos}(\phi_2).\text{Cos}(\alpha_2)$.

Hence in general the joint antenna discrimination relative to the worst case is given by

$$\Delta(D) = 25\text{Log}[\text{Cos}^{-1}(\text{Cos}(\phi_1).\text{Cos}(\alpha_1)).\text{Cos}^{-1}(\text{Cos}(\phi_2).\text{Cos}(\alpha_2))] - 50 \text{ dB} \quad \ldots \text{(iv)}$$

Since g operates to a geostationary satellite ϕ_1 and α_1 will remain sensibly constant with time. By contrast, ℓ will track the LEO satellite so ϕ_2 and α_2 will vary fairly rapidly with time. Assuming that in earth station transmission and reception are disabled when ϕ_2 falls below 10^o, then the worst instants will happen at times when ℓ both creates and receives interference at $\phi_2 = 10^o$ and $\alpha_2 = 0^o$ - ie for <cℓd = 10^o. These circumstances will occur for only a small proportion of the time. For almost all of the time ϕ_2 and α_2 will have larger values, but whenever these values are such that 29 - 25Log(<cℓd) would be less than -10 dBi, no further discrimination should be assumed. In other words, for any given values of ϕ_1 and α_1, the maximum value of Δ(D) occurs whenever <cℓd is greater than 36.3^o; however, such circumstances will occur for the majority of the time.

In Figure 3, values of Δ(D) are plotted for values of ϕ_1 between 10^o and 90^o and α_1 between 0^o and 180^o, using two ordinate scales, one corresponding to <cℓd = 10^o and the other corresponding to <cℓd > 36.3^o. This indicates that for the majority of the time the C/I values for interferences from g to ℓ and from ℓ to g will be between 14 dB and 28 dB (depending on the location of the GSO network earth station) greater than the figures calculated using equation (i) in section 3.1. The distances for acceptable interference will therefore be correspondingly smaller than those in Tables 1A and 1B. Hence, although the distances in Tables 1A and 1B could be used as 'coordination' distances, both coordinating parties would have the reassurance that the interference would be much lower than the 'threshold' value for most of the time.

Figure 3 also shows that, provided the LEO feeder-link earth station (ℓ) is located such that α_1 is greater than about 35^o, more than 14 dB of additional discrimination against interference will always exist in both directions of transmission, and for most of the time the extra discrimination will be 28 dB. Furthermore, for those cases where the FSS/GSO earth station operates at an elevation greater than about 25^o, the additional discrimination will exceed 24 dB for most of the time even for α_1 within +/-35^o.

Introducing Δ(D) into equations (i) and (ii) it can be shown that even 14 dB would be enough to reduce 15 of the 28 distances in Table 6 exceeding 130 km, to less than 130 km, and that 24 dB would reduce all but 9 of the 36 distances (including all but two of those for which the GSO/FSS is the 'wanted' network) to less than 100 km. And it should be noted that no account has been taken of earth station site shielding in the foregoing analyses; in many practical cases a further 10 to 20 dB of protection from great circle modes of interference can be obtained in this way and used to facilitate coordination.

Therefore a general conclusion is that, if reverse band working was adopted, the coordination distance between a proposed LEO/MSS feeder-link earth station and an existing GSO/FSS network earth station operating at an elevation angle of 10^o or greater would usually be within 130 km, if the former was planned to be located more than 35^o from the azimuth bearing of the latter. Even in cases where the preferred location for the feeder-link station lies on or near the azimuth pointing direction of the GSO/FSS station, the coordination distance is unlikely to exceed 300 km. Finally, in all cases the interference will vary between the level at the coordination threshold and a level 14 dB lower, as the feeder-station pointing direction changes with the motion of the LEO satellite.

Thus the UK considers that operation of the LEO/MSS feeder-links in reverse band mode would be a viable way of facilitating frequency sharing with conventional GSO/FSS carriers, except perhaps in bands heavily used for VSAT and other small dish applications, in areas where large numbers of such terminals are likely to be deployed. Provided coordination distances of the orders indicated in the previous paragraph were borne in mind in locating the feeder-link earth stations, then the only respect in which RR2613 would need to be implemented would be to arrange for the transmissions from each of those stations to be automatically muted whenever its elevation angle fell below 10°. Alternatively the feeder-station antennas could be inhibited from pointing below 10°. No special facilities would be necessary aboard the LEO satellites. Since the GSO/FSS earth station antennas would also operate only at elevations above 10°, these arrangements would additionally ensure that unacceptable interference into the feeder-station antennas would be avoided.

In view of the difficulties identified in sections 1.4 and 1.7 of this Report and elsewhere of sharing frequency bands between GSO/FSS networks and LEO/MSS feeder-links in the normal mode, it is considered that the study summarised in this paper has shown reverse band operation of the LEO/MSS feeder-links to be a feasible way of avoiding such difficulties.

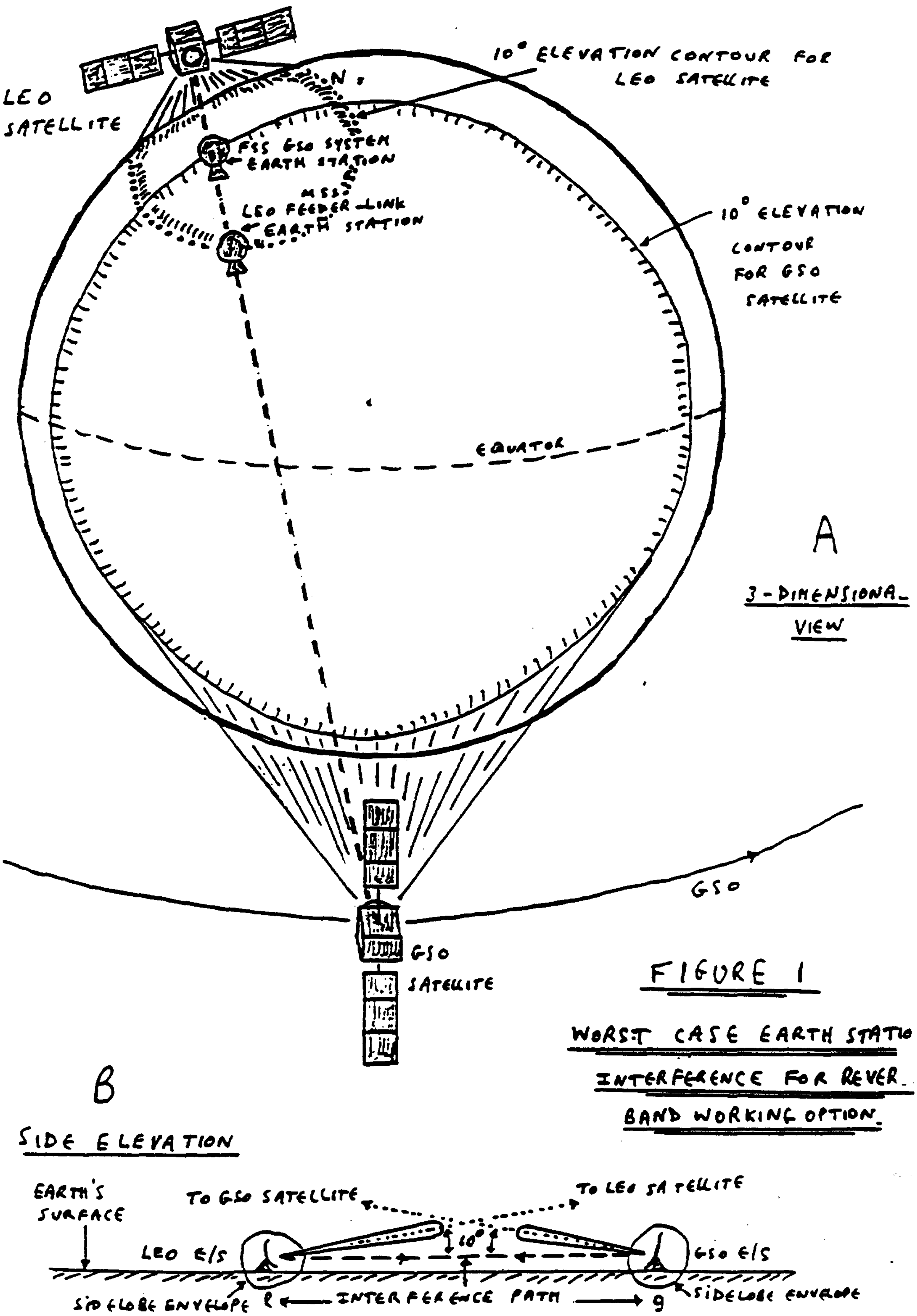


FIGURE 1

WORST CASE EARTH STATION INTERFERENCE FOR REVERSE BAND WORKING OPTION.

$GO = 42162$ km

$XO = 6376$ km

$LO = (6376 + h)$ km

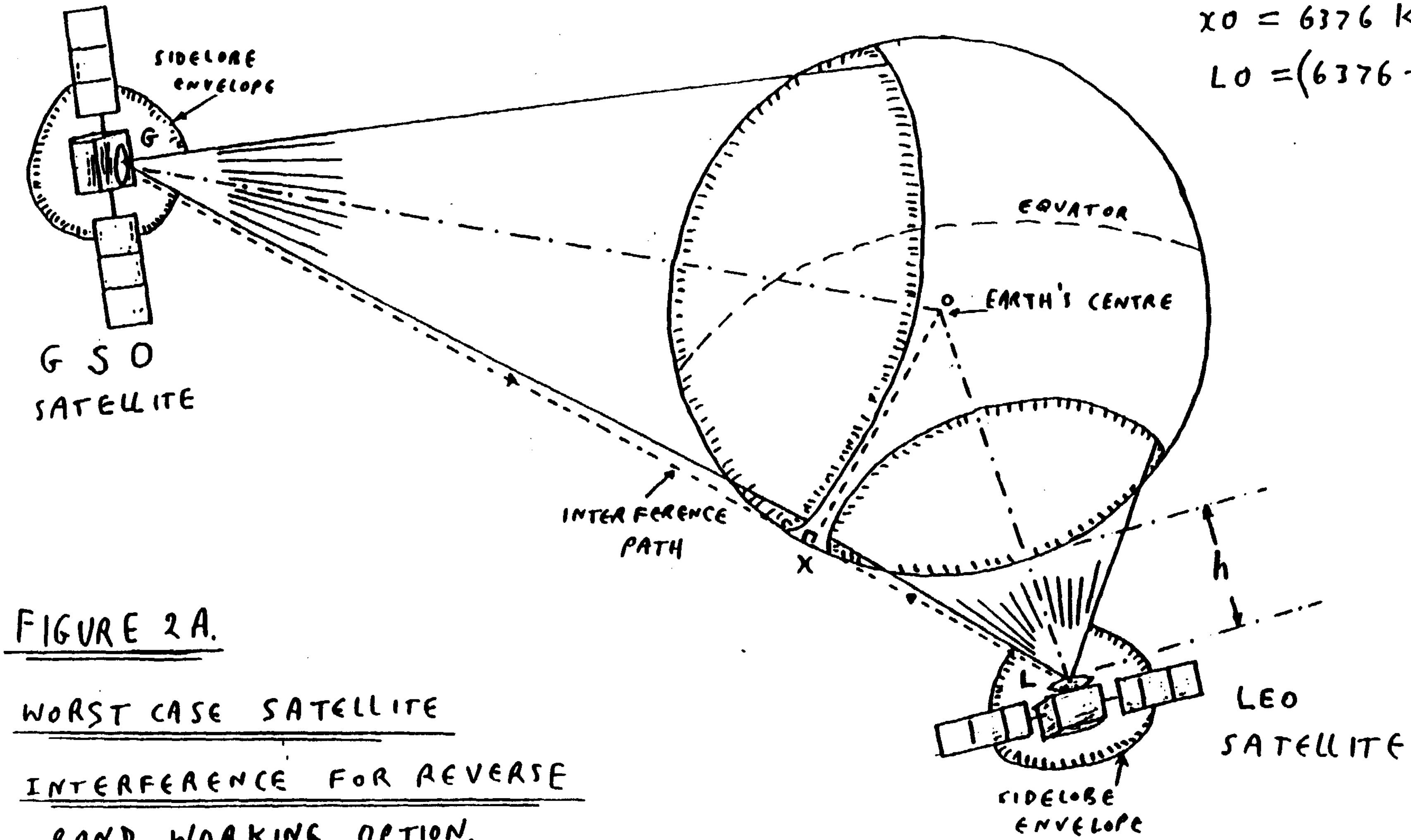


FIGURE 2A.

WORST CASE SATELLITE INTERFERENCE FOR REVERSE BAND WORKING OPTION, ASSUMING GLOBAL BEAMS

$$GL = 41677.1 + \sqrt{(6376 + h)^2 - 40653376} \text{ km}$$

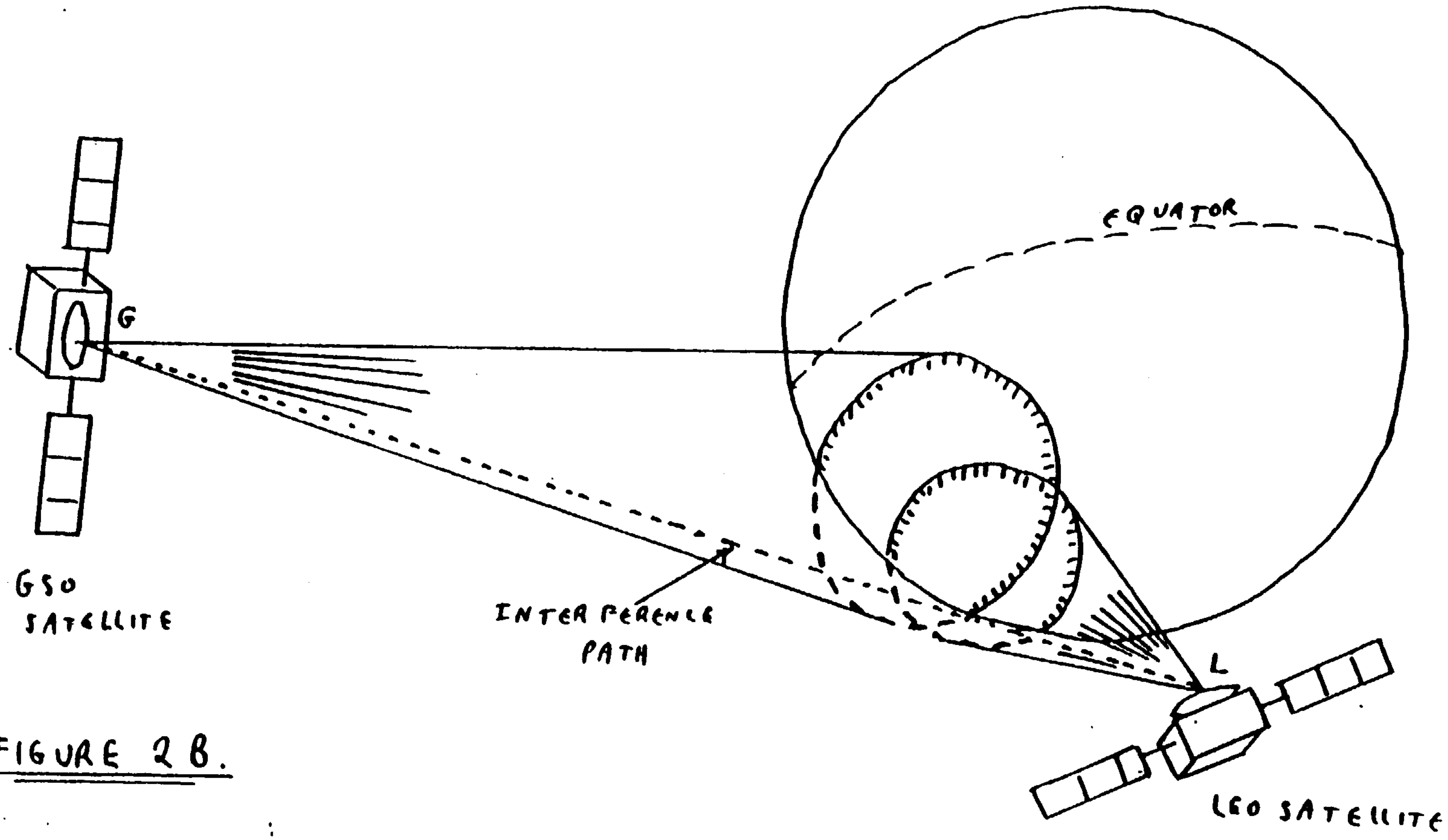


FIGURE 2B.

WORST CASE SATELLITE INTERFERENCE FOR REVERSE BAND WORKING OPTION, ASSUMING SPOT BEAMS.

AGAIN, $GL = 41677.1 + \sqrt{(6376 + h)^2 - 40653376}$ km

where h = HEIGHT OF LEO.

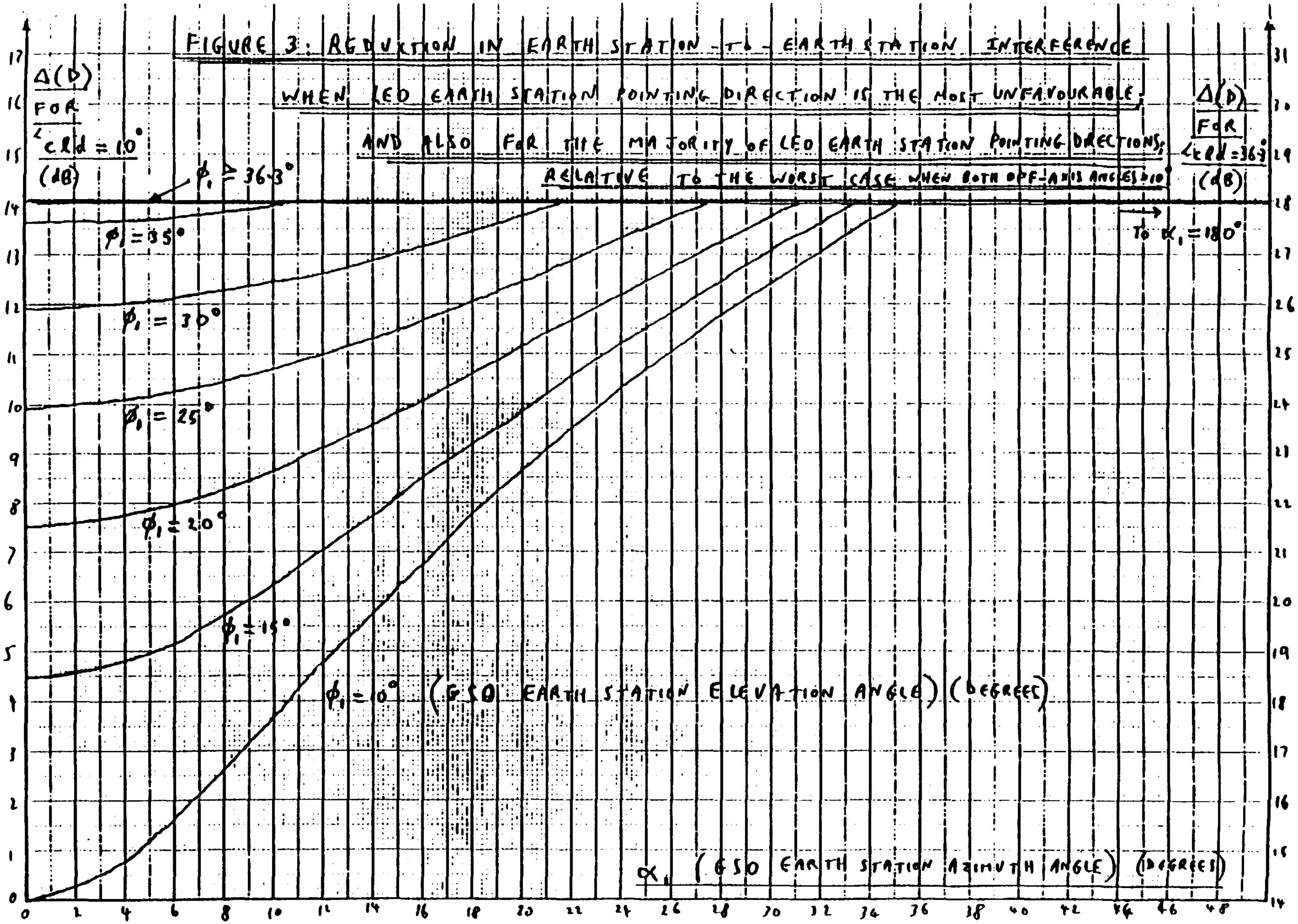
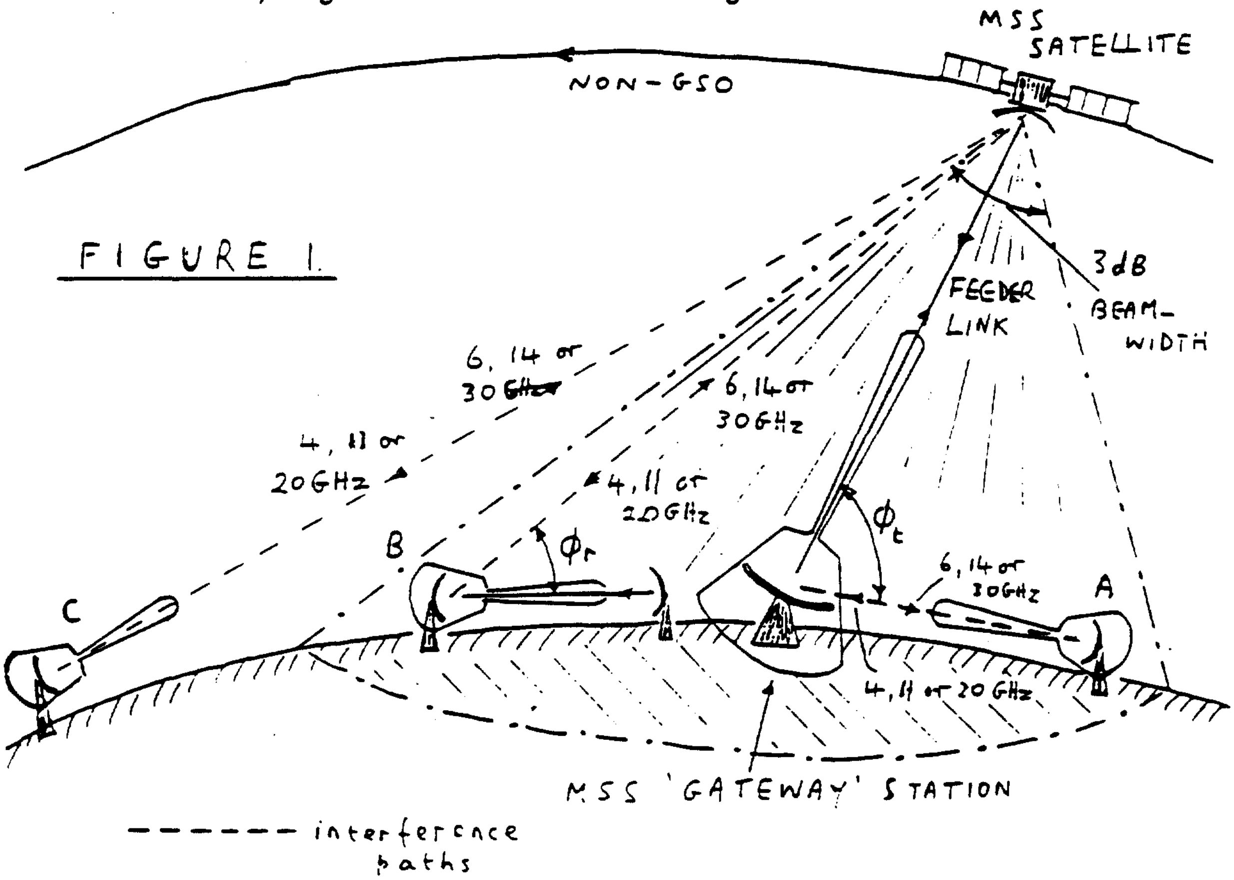


FIGURE 3: REDUCTION IN EARTH STATION - TO - EARTH STATION INTERFERENCE
WHEN LEO EARTH STATION POINTING DIRECTION IS THE MOST UNFAVOURABLE,
AND ALSO FOR THE MAJORITY OF LEO EARTH STATION POINTING DIRECTIONS,
RELATIVE TO THE WORST CASE WHEN BOTH OFF-AXIS ANGLES = 10°
Δ(D) FOR ∠cRd = 10° (dB)
Δ(D) FOR ∠cRd = 36.3° (dB)
φ1 ≥ 36.3°
φ1 = 35°
φ1 = 30°
φ1 = 25°
φ1 = 20°
φ1 = 15°
φ1 = 10° (GSO EARTH STATION ELEVATION ANGLE) (DEGREES)
To α1 = 180°
α1 (GSO EARTH STATION AZIMUTH ANGLE) (DEGREES)

2. SHARING BETWEEN NON-GSO MSS FEEDER LINKS AND THE FIXED SERVICE

2.1 Interference Modes

ITU RR 22 allows FSS frequency allocations to be used for feeder-links of other services but at present there is no worldwide agreement on which particular frequency ranges withi those allocations should be used for non-GSO MSS feeder links. Therefore for the time being, since the great majority of the FSS allocations are shared with the FS on a co-Primary basis, it is necessary to consider C-band, Ku-band and Ka-band possibilities for the non-GSO MSS feeder-links. (The small proportions of the FSS bands not shared with the FS are either not available to the FSS on a worldwide basis, or are likely to be heavily used for VSAT and other small dish services which will be incompatible with non-GSO MSS feeder-links). Fig 1 below illustrates the sharing scenario:



A, B and C are terrestrial microwave radio-relay terminals.

In general terrestrial radio-relay links use each frequency allocation shared with the FSS both for transmitting and for receiving, whereas with rare exceptions the FSS earth static transmissions are confined to the earth-to-space bands (6, 14 and 30 GHz) and the FSS satellite transmissions are confined to the space-to-earth bands (4, 11 and 20 GHz). Therefore, assuming that the MSS feeder-links use the FSS bands as currently allocate interference to FS receiving terminals from the satellites will occur at 4 GHz, 11 GHz or 20 GHz, while interference from the earth stations will occur at 6 GHz, 14 GHz or 30 GHz. Correspondingly interference from FS terminals to the MSS satellites will occur at 6 GHz, 14 GHz or 30 GHz, while interference to the MSS gateway stations will occur at 4 GHz, 11 GHz or 20 GHz.

The possibility of the MSS feeder-links operating in reverse-band mode is considered in section 2.6.

In Fig 1 interference between the main beam of an MSS gateway station and FS terminal A is shown occurring at ϕ_t degrees relative to the principal axis of the gateway antenna. The worst case will occur if the azimuth bearing of the gateway antenna is aligned with the main beam of the FS terminal, and the gateway antenna is operating at its minimum elevation angle (usually 10°) - ie when ϕ_t = 10°. Note that these circumstances may never occur, and that even if they do, they will only occur for a small proportion of the time since the gateway antenna will track the motion of the non-GSO satellites.

Interferences between the satellite and the sidelobes of terrestrial radio-relay terminal B, and between the satellite and the main beam of terminal C are also shown. For the instant illustrated, the impact of the interference to-and-from terminal B will be reduced by the discrimination of terminal B's antenna at ϕ_r degrees off-axis. No such protection is available to terminal C, but in most cases, since the non-GSO satellites will use spot beam antennas for their feeder-links, some satellite antenna discrimination will be available. However, since the instance of direct coupling between the main beams of both satellite and radio-relay terminal cannot be precluded at this stage, it must be addressed. Here again the level of interference in both directions will vary as the non-GSO satellite progresses round its orbit, and the worst cases will occur only for small proportions of time

2.2 Carrier Parameters

At the time of writing the only non-GSO MSS feeder-link parameters available to the authors are those listed in Table 1(b) on page 167 of Document ITU-R 4A/181, except tha those for Ka-band have been updated as a result of information made available by IRIDIUM. Three sets of carrier parameters have been extracted from that table, and are given in Table 1 below :-

Table 1

Car No.	Origin	Orbit	Freq Band	Car Type	Band width (kHz)	Sat Rec Gain (dBi)	Sat Trans Gain (dBi)	Sat EIRP (dBW)	Earth Stn EIRP (dBW)	Earth Stn Tran Gain (dBi)	Earth Stn Rec Gain (dBi)	Clear Air C/N (dB)	Single Entry Interf Criteric- *
1	INMARSAT -C HEIGHT SCALED	LEO 765 (km)	C	0.6 kbit/s BPSK	0.72	15.0	15.0	-48.1	28.8	54.0	49.2	6.2	6% of total noise
2	JIWP-92 plus 10 dB	LEO 765 (km)	Ku	PCN TDMA-FDMA	126.0	6.0	6.0	-2.5	54.8	51.3	49.2	5.9	6% o total noise
3	IRIDIUM	LEO 780 (km)	Ka	QPSK 2/3 FEC	3090.0	29.3	23.7	13.5	43.2	55.3	53.0	up 6.0 dn 15.0	6% o total noise

* ITU-R Rec.523

Parameters of a number of FS carriers are in ITU-R Recommendation 758 (1992 version). These include carriers for frequencies below 3 GHz and above 10 GHz, but unfortunately not for the 4 and 6 GHz bands. Pending the availability to the authors of C-band FS carrier parameters, those quoted in Rec.758 for the 2 GHz band are used here, since the fade margins are not likely to be substantially different from those at C-band.

Six sets of FS carrier parameters have been extracted from Annex 2 to Rec.758, two for analogue TV and four for digital telephony and data, as shown in Table 2.

Table 2

Carrier Number	Frequency Band	Carrier Type	Bandwidth (kHz)	Net Antenna Transmit Gain (dBi)	Net Antenna Receive Gain (dBi)	EIRP (dBW)	Thermal Noise in Recvr B/W (dBW)	Single-Entry Interf Criterion **
4	C*	625 line PAL TV	40000	31.0	31.0	39.0	-118	13 dB below Rec Thml Noise
5	C*	4-PSK 8 mbit/s	4000	29.0	29.0	30.0	-133	13 dB below Rec Thml Noise
6	Ku	625 line PAL TV	29000	42.0	42.0	52.0	-121	13 dB below Rec Thml Noise
7	Ku	4-PSK 16 mbit/s	4000	49.0	49.0	45.0	-128	13 dB below Rec Thml Noise
8	Ka	4-PSK 140 mbit/s	68000	41.0	41.0	31.0	-119	13 dB below Rec Thm' Noise
9	Ka	FSK 8 mbit/s	16400	47.0	47.0	37.0	-122.6	13 dB below Rec Thm Noise

* Actually 2 GHz ** Long-term, allows for other entries.

2.3 Antenna Radiation Patterns

For the MSS feeder-link antennas it is assumed that the sidelobes will conform to ITU-R Rec.580, ie

$G_{slm} = 29 - 25\log(\phi)$ dBi for $1° < \phi \leq 36.3°$ and
$G_{slm} = -10$ dBi for $\phi > 36.3°$

Since these antennas will never operate closer than 10° with respect to the direction of a radio-relay receive or transmit terminal, the main beam and first sidelobe patterns are not significant for the present paper (although the on-axis gain is significant).

For the fixed service antennas the reference sidelobe pattern described in ITU-R Rec. 699 is used here :-

$$G_{slt} = 52 - 10Log\left(\frac{D}{\lambda}\right) - 25Log(\phi)\ dBi\ \ for\ \phi_1 < \phi \leq \phi_2 \quad \text{and}$$

$$G_{slt} = 0\ dBi \qquad for\ \phi > \phi_2$$

$$where\ \phi_1 = \frac{100\lambda}{D}\ and\ \phi_2\ is\ given\ by\ 52 - 10Log\left(\frac{D}{\lambda}\right) - 25Log(\phi_2) = 0$$

For the frequencies and dish sizes of interest Table 3 gives the relevant gains :-

Table 3

Frequency (GHz)	Wavelength (λ metres)	Dish Diameter (m)	$\therefore\ \phi_1$ (degrees)	$\therefore\ \phi_2$ (degrees)	G_{slt} $\therefore$ Gain at ϕ_1 (dBi)	G_{slt} $\therefore$ Gain Beyond ϕ_2 (dBi)
4	0.075	1.1	6.82	41.1	19.5	0
6	0.05	0.6	8.33	44.5	18.2	0
11	0.0273	1.4	2.0	24.9	27.4	0
14	0.0214	2.5	0.86	17.9	33.0	0
20	0.015	0.7	2.14	25.8	27.0	0
30	0.010	0.9	1.11	19.9	31.3	0

The sidelobe radiation patterns are plotted in Figure 2

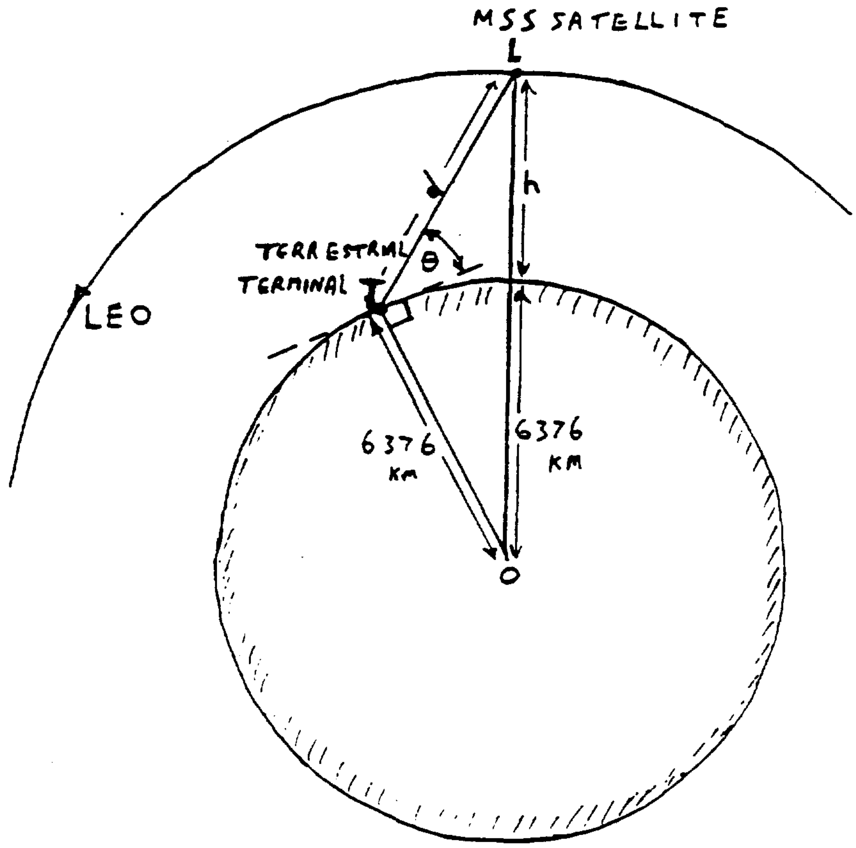
2.4 Interference between MSS Satellites and Terrestrial Radio-Relay Stations

2.4.1 **Interference from Satellite to Radio-Relay Station**

ITU-R Rec.358, revised in recent months, sets limits on the power flux density (pfd) in any 4 kHz (or 1 MHz) band at the surface of the Earth produced by satellites in the FSS using the same frequency bands as line-of-sight radio-relay systems. Since in the worst case the lower the angle, relative to the Earth's surface, that the interference arrives at a radio-relay terminal, the lower the discrimination afforded by that terminal's antenna pattern, the pfd limits are expressed as a function of the angle of arrival (θ).

In the MSS feeder-link carrier examples given in section 2.2 the satellite orbit is circular, with a height (h) of 765 km.

Figure 3



From the geometry of Figure 3

$$d = 1000\left(\frac{6376 + h}{Cos(\theta)}\right).Cos\left\{\theta + Sin^{-1}\left[\frac{6376.Cos(\theta)}{6376 + h}\right]\right\} \; metres \qquad \text{..................(i)}$$

Also, since the MSS carriers will have relatively 'flat' RF spectra, the pfd incident on terrestrial terminal (T) per 4 kHz is given by :-

$$pfd = EIRP_{satellite} - 10Log\left(4\pi d^2\right) - 10lOG\left(\frac{Interfering\ carrier\ bandwidth\ in\ kHz}{4}\right) \text{ dB/4kHz} \qquad \text{..........(ii)}$$

using the satellite EIRPs in Table 1.

Table 4 compares the maximum pfd values calculated from equations (i) and (ii), with the limits in Rec.358.

Table 4

Interfering Carriers	Frequency Band	Arrival Angle (degrees)	Value of d (m x 10^5)	Calculated Interfering pfd ($dBW/m^2/4$ kHz)	Rec.358 pfd Limit ($dBW/m^2/4kHz$)
1	C	0	32.16	-181.79	-152
		5	27.08	-180.30	-152
		25	15.01	-175.17	-142
		90	7.65	-168.72	-142
2	Ku	0	32.16	-158.62	-150
		5	27.08	-157.13	-150
		25	15.01	-152.00	-140
		90	7.65	-145.55	-140
3	Ka	0	32.16	-132.5/1 MHz	-115/1 MHz
		5	27.08	-131.1/1 MHz	-115/1MHz
		25	15.01	-125.9/1 MHz	-105/1 MHz
		90	7.80	-119.5/1 MHz	-105/1 MHz

Since all the calculated pfd levels are comfortably within the prescribed limits it seems unlikely that the down-path MSS feeder-links will be a barrier to frequency sharing.

2.4.2 Interference from Radio-Relay Station to MSS satellite

Clearly, the worst case is when, instantaneously, a radio-relay terminal illuminates the satellite with its main beam (ie terminal C in Figure 1) If there is no discrimination by the satellite's receive antenna pattern, then

$$\frac{C}{I} = EIRP_{feeder-station} - EIRP_{radio-relay\ station} \qquad \text{.................................(iii)}$$

Appropriate Protection Ratios (pr) for the MSS feeder-link carriers may be calculated from the equation

$$pr = operating\frac{C}{N} + 10Log\left(\frac{100}{6}\right) - 10Log\left[\frac{Interf\ carrier\ BW}{MSS\ carrier\ BW}\right]\ \text{dB} \qquad \text{.......... (iv)}$$

Note that for the TV carriers only 2MHz p-p energy dispersal bandwidth is assumed.

Substituting the earth station and terrestrial EIRP values into equation (iii) and the C/N values from Table 1 into equation (iv), the two equations are compared in Table 5 below.

Table 5

Interfering FS Carrier Number	Wanted MSS Carrier Number	Calculated $\frac{C}{I}$ (dB)	Protection Ratio (dB)	∴ Discrimination Shortfall (pr - C/I) (dB)
4	1	-10.2	-16.0	-
5	1	-1.2	-19.0	-
6	2	2.8	6.1	3.3
7	2	9.8	3.1	-
8*	3*	12.2 *	4.7*	-
9	3	6.2	10.9	4.7

* Valid only for reverse-band working case.

The discrimination shortfall of 3.3 dB in the case of carrier 6 interfering with carrier 2, and of 4.7 dB for carrier 9 interfering with carrier 3, would be eliminated if the satellite receive beam provided a small amount of discrimination (which will usually be the case in practice), or, in the first case, if the energy dispersal of radio-relay carrier 6 was increased to about 4.3 MHz peak-to-peak. In any case, for the great majority of the time the position of the LEO satellite will be such that the interference from any particular radio-relay terminal will be emitted via the sidelobes of the terminal's antenna radiation pattern, thus reducing the level by up to 40 dB (see table 2 and Figure 2). It is considered unlikely that more than one or two terrestrial terminals will be pointing directly at the LEO satellite at the same time.

Hence, sharing is unlikely to be significantly inhibited by terrestrial link interference to the MSS satellite up-path feeder-links.

2.5 Interference between MSS Gateway Stations and Terrestrial Radio-Relay Stations

2.5.1 Interference from Gateway Stations to Radio-Relay Stations

The interference into radio-relay terminal A in Fig 1 is shown as received by the main beam of the terminal. In general this assumption is pessimistic, since it will usually be practicable to locate the gateway station on a geographical bearing which would ensure that the interference was received by the sidelobes of the terrestrial antenna pattern. Fig 4 illustrates the general situation.

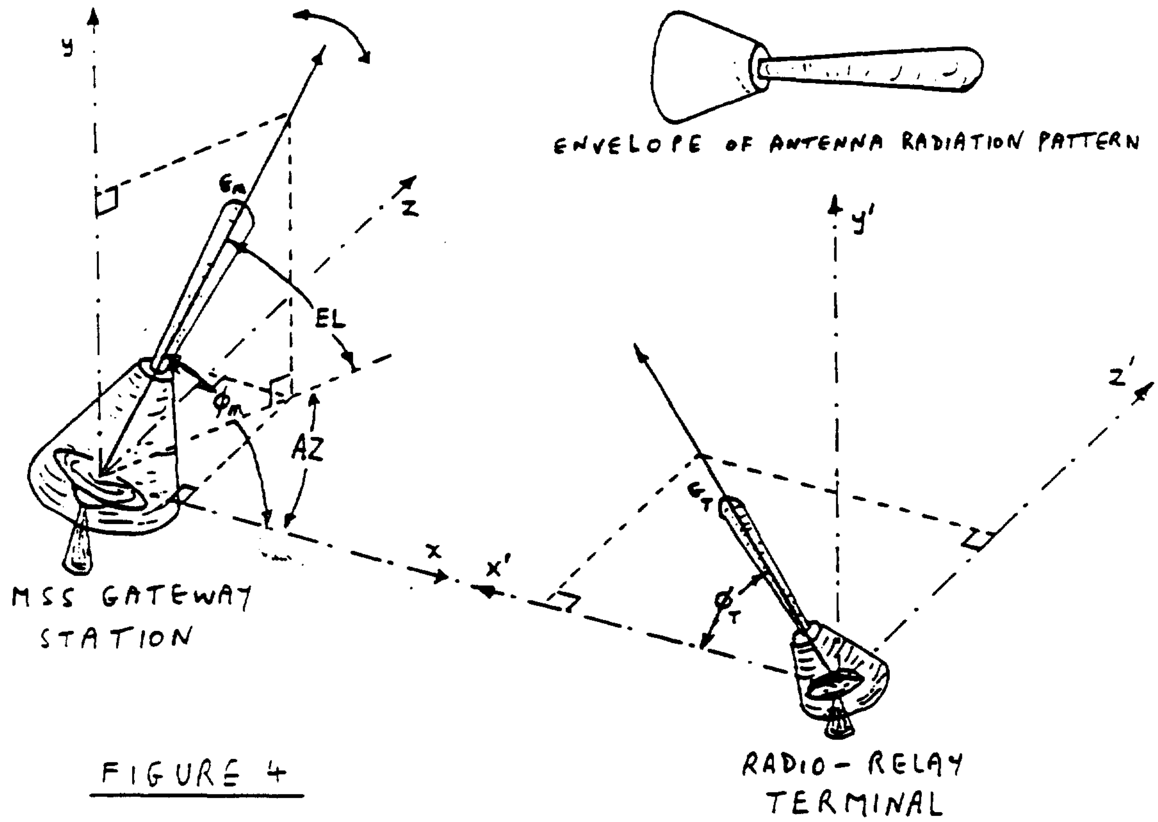


FIGURE 4

The pointing direction of the radio-relay antenna remains fixed in the horizontal plane (or close to it), while the MSS gateway antenna pointing direction varies over a solid angle of up to about 1.8π steradians as it tracks the LEO satellite.

ϕ_m is the off-axis angle between the principal axis of the gateway station's main beam and the line of interference between the two terminals, and from the geometry of the diagram it can be shown that $\phi_m = \mathrm{Cos}^{-1}[\mathrm{Cos(EL).Cos(AZ)}]$ ....(v)

ϕ_t is the bearing of the MSS gateway station with respect to the radio-relay terminal.

In the worst case $\phi_t = 0°$ and at the worst instant AZ = 0° and EL = 10°, assuming that the gateway station does not operate at elevation angles lower than 10°.

Thus from Fig 2, if $\phi_t = 0°$, the antenna discrimination will vary from $(G_m - 4)$ dBi to $(G_m - \{-10\})$ dBi - a 14 dB range - as the gateway antenna tracks its satellites. If $G_m = 54$ dBi, for example, the variation of discrimination with time will be from 50 to 64 dBi. Similarly, if ϕ_t is greater than an angle between 17.9° and 44.5° (depending on frequency), the joint antenna discrimination will vary from $[(G_m - 4) + (G_t - 0)]$ dBi to $[(G_m - \{-10\}) + (G_t - 0)]$ dBi. For typical antenna gains of $G_m = 54$ dBi and $G_t = 41$ dBi (see Tables 1 and 2), the discrimination will vary between 99 and 105 dB.

Clearly, two factors will have a substantial influence on the separation distance (d_{min}) between the two antennas required to keep the interference within an acceptable level:-

- The angle ϕ_r; this will be determined by the geographical location of whichever of the two terminals is the later to be installed (usually the MSS gateway station since in the frequency bands of interest many FS stations already exist, while non-GSO MSS networks have yet to be implemented);

- the proportion of time for which the minimum gateway antenna discrimination exists; it is reasonable to assume that a higher level of interference could be tolerated for small proportions of time than the acceptable level for full-time interference.

Bearing these factors in mind, calculations of d_{min} have been carried out for $\phi_r = 0°$ and for $\phi_r \geq \phi_2$ in Table 3, in each case for $\phi_m = 10°$ and for $\phi_m \geq 36.3°$.

Such calculations require the propagation attenuation over the Earth's surface to be modelled. For specific 'live' cases the topography of the terrain along the interference path would need to be incorporated into the model, taking account of local site shielding at each antenna. This is not practicable in a general study such as the present one, but ITU-R Rec.847 (1992), entitled "Determination of the Coordination Area of an Earth Station Operating with a Geostationary Space Station and Using the same Frequency Band as a System in a Terrestrial Service", describes generally applicable mathematical models for two propagation modes. These are:

- Mode 1 - great circle propagation mechanisms, and
- Mode 2 - scattering from hydrometeors.

The Recommendation models short-term propagation mechanisms in both cases, and it could be argued that their use in calculations where either the interfering or the wanted antenna discrimination varies widely with time is unduly pessimistic. In recognition of this argument only the Mode 1 model is used in the present calculations and, since the non-GSO MSS systems currently being planned are mostly intended for land-mobile and PCN applications, it is assumed that the gateway earth station-to-radio-relay interference paths will be predominantly over land (rather than sea).

Equation (6) of ANNEX 1 to Rec.847 is as follows :-

$$L_b(p) = P_t + G_e + [42 + \Delta G] - P_r(p)$$

where $L_b(p)$ is the minimum permissible transmission loss between two isotropic antennas (in dB),

P_t is the input power level to the transmitting antenna of the interfering station (in dBW)

G_e is the gain of the interfering antenna in the direction of the wanted station (in dBi)

$[42 + \Delta G]$ is the antenna gain of the 'wanted' station in the direction of the interference, and

$P_r(p)$ is the threshold interference level at the terminals of the receiving antenna of the 'wanted' station to be exceeded for no more than p% of the time. p is taken as 0,1 in this analysis.

In the parlance of the present case this equation can be re-written:-

$$L_b(p) = \left[EIRP_{MSS\ carrier} - G_m\right] + G_{sm} + G_{st} - \left[receiver\ thermal\ noise - 13\right] + 10\log\left(\frac{B_t}{B_m}\right) \text{ dB} \quad \text{.......(vi)}$$

where B_t is bandwidth of terrestrial carrier and B_m is bandwidth of MSS carrier.

Combining equations (7), (8) and (10) of Annex 1 to Rec.847 we obtain:-

$$L_b(p) = \sum_{i=1}^{n} \beta_i . d_i + 120 + 20\log(f) + \log(p) + 5p^{0.5} + A_h \text{ dB}$$

where

f = frequency (GHz), and A_h is a parameter to correct for the elevation of the interfering station's horizon relative to the horizontal plane. For present purposes the horizon can be assumed to have zero elevation, for which $A_h = 0$.

$\beta_i(p).d_i$ = the attenuation of the i^{th} section of the interference path (d), assuming that the path comprises a sequence of sections of differing radio-climatic zones. There are four such zone types - coastal land, other land, cold seas, warm seas.

In keeping with the earlier argument, for present purposes the entire interference path is taken as being in Zone A_2 (land, other than coastal land). Hence we may write :-

$$L_b(0.1) = \beta(0.1).d + 20Log(f) + 120.581 \text{ dB} \quad \text{.........} \quad \text{...........(vii)}$$

Equation (11) of ANNEX 1 to Rec.847 defines $\beta(p)$ as

$$\beta(p) = 0.01 + \beta_{dt}(p) + \beta_0 + \beta_{wt} \text{ dB/km}$$

For Zone A_2, $\beta_{dt}(p) = 0.04 + 0.05Log(f) + 0.16p^{0.1}$

$$\therefore \beta_{dt}(0.1) = 0.167 + 0.05Log(f)$$

For f < 57 GHz, $\beta_0 = \left[7.19x10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{(f-57)^2 + 1.5}\right] f^2 x10^{-3}$ dB/km and for Zone A_2,

$$\beta_{vt} = \left[0.06575 + \frac{3.6}{(f-22.2)^2+8.5} + \frac{10.6}{(f-183.3)^2+9.0} + \frac{8.9}{(f-325.4)^2+26.3}\right]$$

$$x\, f^2 x 7.5 x 10^{-4} \quad \text{dB/km}$$

Substituting for f in these equations yields the values of $L_b(0.1)$ in Table 6.

Table 6

Frequency f (GHz)	$\beta_{dz}(0.1)$ (dB/km)	β_0 (dB/km)	β_{vt} (dB/km)	$\therefore \beta(0.1)$ (dB/km)	$L_b(0.1)$(dB) [X + Y.d]
4	0.1971	0.00615	0.00092	0.21417	132.6 + 0.21417.c
6	0.2059	0.00638	0.00214	0.22442	136.1 + 0.22442.d
11	0.2191	0.00722	0.00845	0.24477	141.4 + 0.24477.d
14	0.2243	0.00800	0.01672	0.25902	143.5 + 0.25902.d
20	0.2321	0.01037	0.10083	0.35330	146.6 + 0.35330.d
30	0.2409	0.01849	0.07979	0.34918	150.1 + 0.34918.d

and, substituting for $L_b(p)$ in equation (vi) we get :-

$$d_{min} = \frac{1}{Y}\left[EIRP_{MSS} - G_m + G_{sim} + G_{sli} - Rec.Th.Noise + 13 + 10Log\left(\frac{B_i}{B_m}\right) - X\right] \text{ km } \quad ...(viii)$$

Then, inserting the appropriate values from Tables 1 and 2 and Fig 2 yields Table 7

Table 7

Intrf Car	wntd Car	Freq GHz	$\frac{1}{\gamma} \cdot$	[EIRP +MSS dBW	ϕ_m deg	ϕ_i deg	$-G_m$ dBi	$+G_{\mu m}$ dBi	$+G_{\mu i}$ dBi	− Rec Thml noise dBW	$+ 10 \log\left(\frac{B_i}{B_m}\right)$	− X	+13]	[illegible]
1	4	6	4.45	28.8	10	0	54.0	4.0	31.0	-118	47.4	136.1	13	232
					10	$\geq \phi_2$		4.0	0.0					94.0
					≥ 36.3	0		-10.0	31.0					169
					≥ 36.3	$\geq \phi_2$		-10.0	0.0					57.5
1	5	6	4.45	28.8	10	0	54.0	4.0	29.0	-133	37.4	136.1	13	245
					10	$\geq \phi_2$		4.0	0.0					116
					≥ 36.3	0		-10	29.0					183
					≥ 36.3	$\geq \phi_2$		-10	0.0					102
2	6	14	3.86	54.8	10	0	51.3	4.0	42.0	-121	23.6	143.5	13	245
					10	$\geq \phi_2$		4.0	0.0					83.4
					≥ 36.3	0		-10.0	42.0					191
					≥ 36.3	$\geq \phi_2$		-10.0	0.0					61.0
2	7	14	3.86	54.8	10	0	51.3	4.0	49.0	-128	15.0	143.5	13	266
					10	$\geq \phi_2$		4.0	0.0					194
					≥ 36.3	0		-10.0	49.0					212
					≥ 36.3	$\geq \phi_2$		-10.0	0.0					50.7
3	8	30	2.86	43.2	10	0	55.3	4.0	41.0	-119	13.4	150.1	13	108.[illegible]
					10	$\geq \phi_2$		4.0	0.0					5.9
					≥ 36.3	0		-10.0	41.0					101.2
					≥ 36.3	$\geq \phi_2$		-10.0	0.0					1.2
3	9	30	2.86	43.2	10	0	55.5	4.0	47.0	-123	7.2	150.1	13	110.1
					10	$\geq \phi_2$		4.0	0.0					4.5
					36.3	0		-10.0	47.0					103
					36.3	$\geq \phi_2$		-10.0	0.0					1.0

[* Allows for multiple interference entries and is slightly pessimistic since inter-MSS carrier guardbands are ignored.]

Noting that a few of the d_{min} values calculated using the Rec. 847 method were quite small, and could correspond to cases where the two antennas are within sight of each other, it was considered prudent to calculate d_{min} in those cases assuming free space line-of-sight propagation conditions, ie that :-

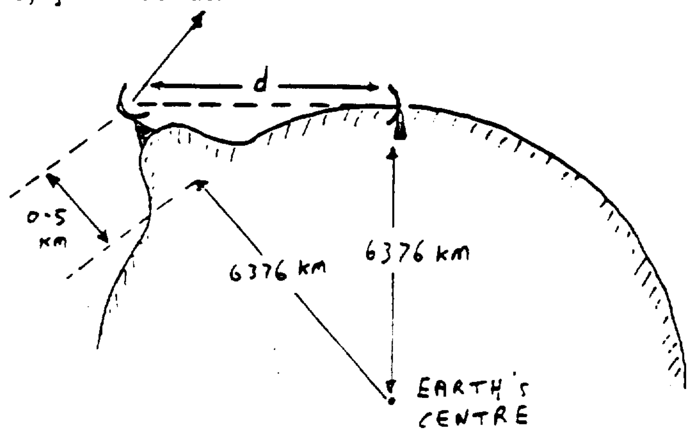
$$L_b(p) = 92.44 + 20\text{Log}(f) + 20\ \text{Log}(d_{min})\ \text{dB}\quad \{f \text{ in GHz and } d_{min} \text{ in km}\}.$$

Substituting this expression for $L_b(p)$ in equation (vi) leads to the following equation :-

$$20\text{Log}(d_{min}) = EIRP_{mss} - G_m + G_{slm} + G_{slt} - \text{Rec. Th. noise} + 10\text{Log}(B_t/B_m) - 20\text{Log}(f) - 79.44 \quad \text{.........(ix)}$$

If the difference in altitude above sea level of the MSS gateway station and the radio-relay station is 500 metres - a reasonably conservative assumption - then Figure 5 shows that the two stations will just be within line-of sight of each other (assuming flat terrain) when $d = [(6376.5)^2 - (6376)^2]^{0.5}$ = **80 km.**

Figure 5



Therefore d_{min} for free space loss has been substituted in Table 7 in those cases where the great circle propagation model would otherwise result in a distance less than 80 km, and less than the distance given by free space conditions. In 3 cases the values based on free space loss were well beyond line-of-sight, so a loss rate of 2 dB/km beyond 100 km was substituted to obtain more realistic distances.

ACCEPTABILITY OF d_{min} VALUES IN TABLE 7

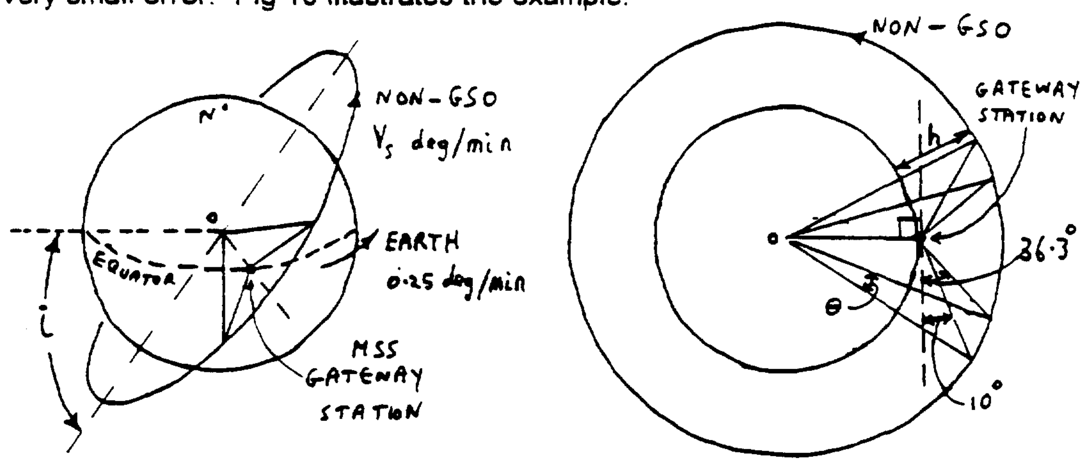
If these values are seen as coordination thresholds, then the worst cases should be considered, and these depend on ϕ_1, the bearing of the MSS gateway station with respect to the location of the radio-relay terminal (see Figure 4). Since the MSS/LEO networks have yet to be installed it would seem feasible to locate the gateway stations to ensure that ϕ_1 exceeds the value of ϕ_2 given in Table 3 for the frequency band of interest. If this is done, then the values in Table 7 suggest that coordination would not usually be necessary for radio-relay terminals more than 200 km from each MSS gateway station.

For the purposes of coordination in those instances where it is necessary it will be helpful to know the variability of the interference with time. This depends on the pointing of the MSS gateway station as it tracks its non-GSO satellites. To obtain an idea of the proportion of time for which ϕ_m (see Figure 4) is small a computer program which, inter-alia, calculates ϕ_m at intervals of 1 second as the non-GSO satellite progresses round its orbit, was run for a simulated period of 400 or 500 days. These runs were arranged to determine the value of 25Log(ϕ_m) for an MSS gateway antenna tracking a **single** non-GSO satellite, assuming that, on each 'pass' the antenna 'picks up' the satellite when ϕ_m = 10° and operates to it continuously until ϕ_m is again equal to 10°, when it hands over to another gateway station. Reference to Figure 2 shows that between ϕ_m = 10° and ϕ_m = 36.4° the sidelobe gain envelope varies from 29 - 25Log(10) = 4 dBi to 29 - 25Log(36.4) = -10 dBi, and that beyond 36.4° it remains at -10 dBi. Therefore by calculating, over a period of many days, the number of 1 second intervals for which 25Log(ϕ_m) lies between 24.5 and 25.5, then between 25.5 and 26.5, then between 26.5 and 27.5 and so on, a histogram may be plotted showing the proportions of time for which each decibel of additional interference reduction will be provided by the discrimination of the gateway antenna's radiation pattern.

The results of these runs are contained in Figures 6, 7 and 8, corresponding to orbit heights of approximately 770 km, 1500 km and 10000 km, which are the approximate heights planned for the IRIDIUM, GLOBALSTAR and INMARSAT Project-21 MEO systems. The approximate orbit inclinations of these three systems were also used. [In these three Figures the word "theta" corresponds to the symbol ϕ_m used in the text]. The numbers of seconds corresponding to each bar of each histogram should not be taken literally, since in practice the MSS gateway station will operate to other satellites during the time the satellite in question is not in view, and also because the 'handover' strategy may well differ from the one described above. However, making the (probably pessimistic) assumption that a given gateway station will transmit (and receive) for 100% of the time, these results serve to indicate that the worst interference to terrestrial networks will occur for only a small proportion of time Taking the sum of the histogram bars in each figure to correspond to 100% of time yields Fig 9. From this it appears that, regardless of orbit height. the results in Table 7 for ϕ_m ≥ 36.3° will apply for more than 80% of the time.

Thus a further question arises - ie "typically, how long will it take ϕ_m to move from 10° to 36.3° ?" - in other words, "what is a typical period for which less than the maximum gateway antenna discrimination will last, when it occurs?". This can readily be determined for a case of a gateway station situated on the Equator and the non-GSO satellite passing directly overhead, because the assumption of plane geometry involves only a very small error. Fig 10 illustrates the example.

Figure 10

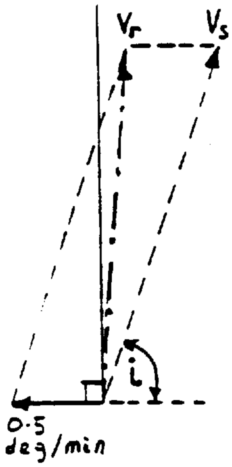


Three dimensional view

View in orbit plane

The angle of interest (θ) can be determined from the geometry :-

$$\theta = 26.3 - Sin^{-1}\left[\frac{6279.1}{6376+h}\right] + Sin^{-1}\left[\frac{5138.6}{6376+h}\right] \text{ degrees} \qquad \text{.....................(x)}$$



The velocity with which the non-GSO satellite traverses θ is the relative velocity of the satellite with respect to the Earth (V_r) :-

The absolute velocity of the satellite (V_S) is given by :-

$$V_s = 0.25\left(\frac{42162}{6376+h}\right)^{\frac{3}{2}} \text{ deg/ min} \qquad \text{..............................(xi)}$$

and from the vector diagram

$$|V_r| = \left[(0.25)^2 + (V_s)^2 - 2x0.25xV_sxCos(i)\right]^{0.5} \text{ deg/min} \qquad \text{.............(xii)}$$

Then the duration of traverse from ϕ_m = 10° to ϕ_m = 36.3° is given by $\frac{\theta}{|V_r|}$ minutes

........(xiii)

Table 8 was produced using equations (x) to (xiii) :-

Table 8

ORBIT			Traverse Angle	Absolute Velocity of Satellite	Velocity Relative to Earth	Duration of Traverse
Type	Height (km)	Inclination i (deg)	θ (deg)	V_S deg/min	V_r deg/min	minutes
IRIDIUM	770	80	10.79	3.583	3.548	3.040
GLOBALSTAR	1500	52	14.16	3.096	2.949	4.80
INMARSAT P-21	10000	50	22.04	1.033	0.893	24.68

The values of d_{min} in Table 7 indicate that the coordination of an MSS non-GSO gateway station with a radio-relay terminal should be no more difficult than the coordination of a conventional FSS earth station with the radio-relay terminal. Provided that care is taken in the selection of the site for the gateway station, typical coordination distances would be less than 200 km even if based on the (short-term) worst pointing direction of the gateway antenna.

In view of the facts that (a) for the majority of the time the pointing directions of the gateway antenna will be such that its interference to the radio-relay terminal will be 14 dB below the maximum (see Fig 9), and (b) that the periods during which the interference will rise above the '-14 dB level' will last for only a few minutes (see Table 8), it would seem practicable to use the distances corresponding to the '-14 dB level' as coordination distances. This possibility is enhanced by the fact that the interference levels themselves are calculated using a short-term propagation model. Using this rational Table 7 suggests that typical coordination distances would be less than 100 km.

Table 9

Interf Carrier	Wanted Carrier	Freq Band	$\frac{1}{Y}$	[EIRP FS (dBW)	− G_t (dBi)	ϕ_t (deg)	ϕ_m (deg)	+ G_{stt} (dBi)	+ G_{stm} (dBi)	− EIRP Sat (dBW)	+ Path-loss (dB)	− G_m (dBi)	+ $\frac{C}{N}$ (dB)	+ $10\log\left(\frac{B_m}{B_t}\right)$	− X	+ 12.2]	∴ d_{min} (km)
4	1	C	4.669	39.0	31.0	0	10	31.0	4	-48.1	196.5	49.2	6.2	-47.4	132.6	12.2	358.6
						0	≥ 36.3	31.0	-10								293.2
						$\geq \phi_2$	10	0	4								213.8
						$\geq \phi_2$	≥ 36.3	0	-10								149.5
5	1	C	4.669	30.0	29.0	0	10	29.0	4	-48.1	196.5	49.2	6.2	-37.4	132.6	12.2	363.2
						0	≥ 36.3	29.0	-10								297.9
						$\geq \phi_2$	10	0	4								227.8
						$\geq \phi_2$	≥ 36.3	0	-10								162.8
6	2	Ku	4.085	52.0	42.0	0	10	42.0	4	-2.5	205.3	49.2	5.9	-23.6	141.4	12.2	276.6
						0	≥ 36.3	42.0	-10								219.4
						$\geq \phi_2$	10	0	4								105.0
						$\geq \phi_2$	≥ 36.3	0	-10								97.7
7	2	Ku	4.085	45.0	49.0	0	10	49.0	4	-2.5	205.3	49.2	5.9	-15.0	141.4	12.2	283.1
						0	≥ 36.3	49.0	-10								225.9
						$\geq \phi_2$	10	0	4								62.9
						$\geq \phi_2$	≥ 36.3	0	-10								52.4
8	3	Ka	2.830	31.0	41.0	0	10	41.0	4	13.5	210.5	53.0	15.0	-13.4	146.6	12.2	130.8
						0	≥ 36.3	41.0	-10								91.1
						$\geq \phi_2$	10	0	4								14.7
						$\geq \phi_2$	≥ 36.3	0	-10								1.0
9	3	Ka	2.830	37.0	47.0	0	10	47.0	4	13.5	210.5	53.0	15.0	-7.2	146.6	12.2	206.0
						0	≥ 36.3	47.0	-10								125.7
						$\geq \phi_2$	10	0	4								32.3
						$\geq \phi_2$	≥ 36.3	0	-10								1.6

2.5.2 Interference from Radio-Relay Stations to Gateway Stations

From Figures 1 and 4 it is evident that the mode of interference in this direction is similar to that analysed in section 2.5.1, except that it will occur in the 4, 11 and 20 GHz bands.

Thus equations (vi) becomes:

$$L_b(p) = EIRP_{FS\ carrier} - G_t + G_{slt} + G_{slm} - I \text{ dB} \quad \ldots \quad (xiv)$$

where I is the permissible interference power (in dBW) at the terminals of the gateway antenna and within the MSS carrier bandwidth and the other symbols are as defined earlier in this text.

But $I = C - \frac{C}{I}$ dBW, where C is the MSS carrier power at the gateway antenna terminals

and $\frac{C}{I}$ is the protection ratio for the particular combination of 'wanted' and 'interfering' carriers.

$C = EIRP_{satellite}$ - path loss from GSO + G_m dBW

and $\frac{C}{I} = operating\,\frac{C}{N} + 10Log\left(\frac{100}{6}\right) + 10Log\left(\frac{B_m}{B_i}\right)$ dB

Hence $I = EIRP_{sat} - path\ loss + G_m - \frac{C}{N} - 10Log\left(\frac{B_m}{B_i}\right) - 12.2$ dBW

∴ Substituting for I in equation (xiv) :-

$$L_b(p) = EIRP_{FS} - G_t + G_{slt} + G_{slm} - EIRP_{sat} + path\ loss - G_m + \frac{C}{N} + 10Log\left(\frac{B_m}{B_i}\right) + 12.2 \text{ dB} \quad \ldots \quad (xv)$$

and the values of $L_b(0.1)$ in terms of the interference path length (d) have already been calculated, and are included in Table 6. Using equation (xv) and the appropriate parameters from Tables 1, 2 and 6, an equivalent Table to Table 7 is given here as Table 9.

as in Table 7, the use of the Rec. 847 model for Table 9 led to several values of d_{min} less than 80 km - ie within line-of-sight. In these cases the values were recalculated using free space path loss, and where these exceeded the earlier values but were less than 100 km they were substituted in the d_{min} column. In two cases the values based on free space loss were well beyond line-of-sight, so a loss rate of 2 dB/km beyond 100 km was substituted to obtain more realistic distances.

ACCEPTABILITY OF d_{min} VALUES IN TABLE 9

Table 9 is very similar in form to Table 7, except that the range of d_{min} values is rather wider, containing both shorter and longer distances than Table 7. Since the propagation mode is the same as that for the interference from gateway station to radio-relay station, and the same antenna discrimination mechanisms apply, similar conclusions can be drawn as those drawn in section 2.5.1. However, in view of the wider range of d_{min} values in this case, the same reasoning as used in the last paragraph of section 2.5.1 leads to the conclusion that typical coordination distances would be "less than 150 km" rather than "less than 100 km".

2.6 CONCLUSIONS

2.6.1 Radio-Relay terminals are protected from excessive interference from space stations in the Fixed-Satellite service by power flux density limits prescribed by the ITU-R. These limits can be applied to satellites using non-geostationary, as well as geostationary orbits if they use FSS frequencies shared with the FS. The studies summarised in Section 2.4.1 suggest that down-path non-GSO MSS Feeder links will not exceed the appropriate ITU-R pfd limits.

2.6.2 The calculations in Section 2.4.2 indicate that interferences to the up-path Feeder links of non-GSO MSS satellites from co-frequency emissions from terrestrial radio-relay terminals are unlikely to exceed single-entry criteria based on ITU-R Recommendations for digital FSS carriers.

2.6.3 Based on the analyses in section 2.5.1 it is likely that interference from the MSS gateway stations to radio-relay receive terminals will be within acceptable limits for the great majority of the time for separation distances greater than 100 km, provided that the gateway stations are sited with reasonable angular separations from the principal axes of the radio-relay antennas.

Owing to the tracking motion of the gateway antennas the interference would rise by up to 14 dB for periods of a few minutes aggregating to typically 10% of the time, on occasions when the 0.1% of time reductions in great circle propagation loss happened to coincide with those periods. Precise estimation of the proportions of time for which the coincidences would occur requires statistical analysis, but superficially they would appear to be of the order of 0.01% of time. No site shielding was assumed in the calculations. If coordination distances were based on this worst-case scenario, they would be typically 220 km.

2.6.4 Interference from radio-relay transmit terminals to the MSS gateway stations will be subject to the same antenna discriminations as the interference in the opposite direction, but the range of levels is likely to be somewhat wider. In this case, provided the gateway stations are not located near the principal axes of radio-relay transmit antennas, the interference (without site-shielding) is likely to be tolerable for